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# ON THE MECHANISM OF FREQUENCY-SELECTIVE BIOLOGICAL EFFECTS OF THE EHF RADIATION AND THE WAYS TO INCREASE THEM

V.A. Shashlov

The acoustic maser effect responsible for the generation of acoustoelectric oscillations with the frequency  $5 \cdot 10^{10}$  Hz. was proved to appear in the regions of biological membranes with the energy release  $10^{-9}$  W/mcm<sup>2</sup>. The energy of the EHF radiation interaction with these oscillations is comparable with that of the thermal motion.

The conclusion was made that this very interaction of EHF radiation with the acoustoelectric oscillating modes of biological membranes forms the basis of frequency-selective bioeffects. Based on this mechanism, the ways to increase the efficiency of EHF therapy were suggested. The role of membrane oscillating modes in life processes was considered.

# ON THE MECHANISM OF FREQUENCY-SELECTIVE BIOLOGICAL EFFECTS OF EHF RADIATION AND METHODS OF THEIR AMPLIFICATION

V. A. Shashlov

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*A proof is offered that there is an acoustic maser effect and acoustoelectric oscillations with a frequency  $5 \cdot 10^{10}$  Hz are generated in parts of biological membranes in which the energy release exceeds  $10^{-9}$  W/ $\mu\text{m}^2$ . It is concluded that interaction with these oscillations is the initial physical cause of EHF bioeffects. Methods are proposed for increasing the effectiveness of EHF therapy. The role of acoustoelectric membrane waters in vital processes is examined.*

The fact that radiation with frequency  $\nu \sim 5 \cdot 10^{10}$  Hz with power flux density  $P_g \sim 1$  mW/cm<sup>2</sup> is capable of having an appreciable effect on biological processes has been known for more than 20 years. The results obtained over this period have been collected in a monograph [1] by the discoverers of this phenomenon. Despite such a long period of research and the wide use of EHF therapy in medical practice, the physical nature of this phenomenon remains unknown. The frequency selectivity of the effects is especially amazing: they occur only in individual frequency bands that are separated by  $\delta\nu \sim 10^{-2}$  and within these bands in narrow frequency intervals the distance between which is  $\delta\nu \sim 10^{-4}$  or less. No physical phenomenon that has such a "sharp" frequency response in the EHF band has been discovered in a solid or liquid of nonbiological origin.

We shall describe the mechanism of a primary act of interaction of EHF radiation with biological tissue that explains all characteristics of EHF bioeffects and, on the basis of this mechanism, propose methods for amplification of the effect of EHF radiation on living organisms.

In Part 1, we shall examine a physical system that models individual types of biological membranes and show that conditions for the self-excitation of acoustoelectric (AE) oscillations with the required spectrum are satisfied in that system.

In Part 2, specific examples of membranes are indicated that could serve as a realization of the described AE generator and the energy of EHF-radiation interaction with membrane modes is estimated. Methods for amplifying the effect of EHF radiation on living organisms are pointed out in Part 3. The general biological value of membrane oscillation modes is examined in Part 4. The applied aspects of the results and the main conclusions are presented in the Conclusion.

1. We shall examine a dielectric film with  $\epsilon \sim 10$  and thickness  $d \sim 10^{-6}$  cm (Fig. 1). Selective ion channels, which are capable of passing ions of a certain size, are made in the film with spacing  $b \sim d$ . The channel conductivity  $\rho \sim 10^7$  ions/sec. The medium surrounding the film contains singly charged ions of the required diameter. In passing through the channels, these ions transfer a large portion ( $\eta \geq 0.5$ ) of their energy  $eU \sim 0.1$  eV ( $e$  is the elementary charge and  $U \sim 0.1$  V is the potential difference between the sides of the film) to the subunits that form the narrowest part of the channel. The oscillation frequencies of these subunits are distributed over a wide band  $\Delta\nu \sim \nu_0/2 \sim 2.5 \cdot 10^6$  Hz near frequency  $\nu_0 \sim 5 \cdot 10^{10}$  Hz. The acoustic resistance of the films exceeds by at least 1-2% that of the surrounding medium; the difference in the acoustic resistances of the blades of a periodic grating is approximately the same. The hypersonic-wave velocity in this frequency band  $\nu \sim 10^5$  cm/sec; the attenuation  $\alpha \sim 10^4$  cm<sup>-1</sup>. Note that the attenuation should not exceed this value, since, otherwise, there would be no Mandelstam-Brillouin effect [2].

We shall verify that the number of phonons of a particular type that are created in the film per unit time exceeds all forms of losses of the given phonons over the same time interval.

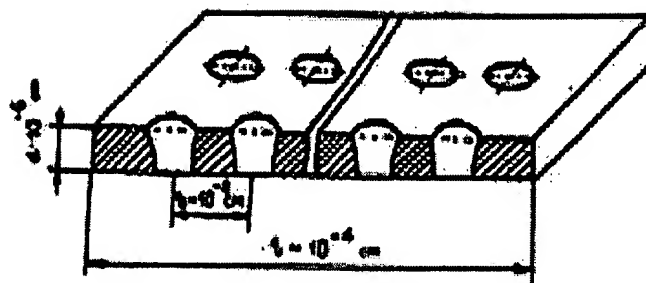


Fig. 1

First of all, we note that for some types of phonons the residence time in the film is determined by the attenuation time. These are the phonons that correspond to hypersonic waves propagated along the film as in a waveguide and are reflected by a periodic grating. The length of these waves satisfies the relations  $\lambda \leq 2d$  and  $b \approx \pi/2$ , i.e.,  $\lambda \approx 2 \cdot 10^{-6}$  cm. Since the reflection coefficient for a single blaze  $\Gamma$  is 1%, hypersonic waves will undergo total reflection at length  $a = \pi/4\Gamma \approx 5 \cdot 10^{-3}$  cm [2]. Since  $2a \leq a^{-1}$ , the waves return to the starting point practically without attenuation. This means that at length  $l \approx 2a \approx 10^{-4}$  cm, standing waves will be produced, whose spectrum  $\nu_{n,m} = \nu(1 \pm \delta\nu_n \pm \delta\nu_m)$ , where  $\nu = v/\lambda \approx 5 \cdot 10^{10}$  Hz is the frequency of the waves,  $n$  and  $m$  are natural numbers,  $\delta\nu_n = \pi/2l \approx 10^{-2}$ , and  $\delta\nu_m = (1/4)(\pi/l)^2 \approx 10^{-4}$ . The rate of disappearance of these phonons from a region with area  $S = l \times l \approx 10^{-8}$  cm<sup>2</sup> will be  $\gamma = \sigma\nu \approx 10^9$  sec<sup>-1</sup>.

On the other hand, the rate of creation of phonons of a certain type can be found by dividing the total number of phonons with a frequency on the order of  $\nu_0$  created in a given region per unit time by the number of different types of phonons that could exist in the given region in frequency band  $\Delta\nu$ . These values are, respectively,  $M = (\omega^2 U / \nu \nu_0) \approx 2.5 \cdot 10^{11}$  sec<sup>-1</sup>,  $1 \approx 8/\nu^2 \approx 10^4$  is the number of ion channels in a given region of the film,  $h$  is Planck's constant, and  $\sigma = (6\pi\nu/V^2)\Delta\nu S \approx 2.5 \cdot 10^4$ , where  $6\pi\nu/V^2 \approx 10^3$  Hz<sup>-1</sup>cm<sup>-2</sup> is the spectral and "volume" phonon density in the two-dimensional case. Thus, the desired rate  $N = M/\rho \approx 10^9$  sec<sup>-1</sup>.

The inequality  $N \geq \gamma$  is satisfied for each film region whose area is not less than  $1 \mu\text{m}^2$ , which means that the self-excitation condition is satisfied. In fact, an arbitrarily selected phonon with frequency  $\nu_{n,m}$  decays (with a probability of 0.5) in time  $\phi = \gamma^{-1} \approx 10^{-9}$  sec, but at least one ( $N\phi \geq 1$ ) phonon with the same frequency, propagation direction, and polarization is created in this time. Consequently, the number of phonons of a given type increases with time, which is consistent with the generation of hypersonic waves.

2. The examined model reflects fairly well the main properties of individual regions of neuron membranes, such as the membranes of nerve endings and Ranvier's nodes - axon regions through which currents of  $\text{Na}^+$  and  $\text{K}^+$  ions flow when a nerve impulse is propagated. Another important example of membranes in which the described effect can be realized are the internal membranes of the mitochondria. In this case, pumping can be accomplished by a current of  $\text{H}^+$  ions or, what is more likely, by the energy of those redox processes with a course on the order of 100 psec. In practice, pumping can be provided by any physicochemical process whose energy-release density exceeds  $\rho eU/b^2 \approx 10^{-6}$  W $\cdot\mu\text{m}^2$ . The periodic grating required to create feedback is apparently inherent in all membranes as a result of their smectic properties: in tough smectic films, the state in which the orientation of the molecules is changed periodically is energetically the lowest.

The described oscillation modes are therefore available in each cell. We shall estimate the energy of interaction of these modes with monochromatic EMF radiation. This energy  $W = \int \vec{p} \cdot \vec{E} dt$ , where  $\vec{p}$  is the dipole moment of the oscillation mode,  $\vec{E}$  is the electric component of the radiation, and  $t$  is the interaction time. For a transverse mode, the dipole moment is numerically equal to the product of the charge  $q = CU \approx 10^{-15}$  C ( $C = \epsilon_0 S/d \approx 10^{-14}$  F is the capacitance of the region occupied by the mode and  $\epsilon_0$  is the dielectric constant) multiplied by the membrane thickness:  $|\vec{p}| = qd \approx$

where  $\delta(\omega_p - \omega_p)$  is the delta function of the difference between the circular frequencies of the oscillation mode and EHF radiation and  $\Phi$  and  $\varphi$  are the angle and phase difference between  $\vec{p}$  and  $\vec{E}$ .

It is apparent from the obtained formula that the interaction energy will differ from zero if the frequency of the EHF radiation coincides with the frequency of the membrane mode. The frequency selectivity of EHF bioeffects is thereby explained.

The interaction energy reaches a maximum when, in addition to  $\omega_p = \omega_p$ , the relations  $|\cos \Phi| = |\cos \varphi| = 1$  and  $\cos \Psi = -\cos \varphi$  are satisfied, which mean that vector  $\vec{E}$  must be collinear with vector  $\vec{p}$  and that these vectors must oscillate in antiphase. The numerical value  $W_{max} \sim 2\pi |\vec{p}| |\vec{E}| = 6 \cdot 10^{-21}$  J. This exceeds by a factor of 1.5 the thermal energy of the oscillation mode ( $kT \sim 4 \cdot 10^{-21}$  J,  $k$  is Boltzmann's constant, and  $T \sim 300$  K is temperature). This means that, despite the nonthermal intensity of the radiation in EHF bioeffects, it increases the energy of the individual oscillation modes by a value that exceeds the energy of their thermal motion. This is entirely sufficient to exert a substantial influence on processes in which the given modes take part. For example, the rate of enzyme reactions at the nodes of a membrane mode can be increased by a factor of  $\exp(W_{max}/kT) = 4.5$ , i.e., by an appreciable amount. Thus, the proposed mechanism "passes" with respect to energetics.

3. Understanding of the mechanism of EHF bioeffects will permit not only the establishment of theoretical foundations for EHF therapy but also the development of methods that will make this therapeutic method even more effective. In particular, EHF bioeffects can be intensified by the introduction of frequency and phase modulation as well as by the use of circularly polarized radiation. The number of oscillation modes for which the interaction energy is maximized will be increased in all of these cases.

Additional amplification of the effects can be achieved by selecting a modulation and polarization-vector-circulation frequency that is equal to the frequency of some membrane process, such as the opening of an ion channel or enzyme inversion. Double resonance occurs in this case, owing to which the given process is selectively amplified. In fact, a method for acting on individual membrane processes appears.

Another possible method for amplification of EHF bioeffects is the use of radiation that consists of phased spectral components whose frequencies coincide with the frequencies of the membrane modes. Such radiation will synchronize the membrane modes, as a result of which short powerful AR-wave impulses will be formed, which are able not only to accelerate biochemical processes but also directly cause structural changes in macromolecules. In fact, with as few as three synchronizing modes, the impulse energy is not less than  $3^2 kT \sim 0.2$  eV, and this energy is sufficient to break hydrogen bonds. This method would be the most effective.

It is well-known that mode synchronization can be accomplished by modulating the parameters of the active medium with frequencies that are equal to the difference frequencies of the resonant modes. In our case, this modulation can be